Formation and coalescence of relativistic binary stars: effect of kick velocity

V. M. Lipunov, K. A. Postnov and M. E. Prokhorov

Sternberg Astronomical Institute, 119899 Moscow, Russia

ABSTRACT

For the first time, using Monte-Carlo calculations of the modern scenario for binary stellar evolution with account for spin evolution of magnetized compact stars (the "Scenario Machine"), we compute the amount of galactic binary pulsars with different companion types (OB-star, white dwarf (WD), neutron star (NS), black hole (BH), or planet) assuming various phenomenological distributions for kick velocities of newborn NS. We demonstrate a strong dependence of the binary pulsar population fractions relative to single pulsars on the mean kick velocity and found an optimal kick velocity of 150-200 km/s.

We also investigate how the merging rates of relativistic binary stars (NS+NS, NS+BH, BH+BH) depend on the kick velocity. We show that the BH+BH merging may occur, depending on parameters of BH formation, at a rate of one per 200,000 – 500,000 years in a Milky Way type galaxy. The NS+NS merging rate R_{ns} is found to be 1 per $\sim 3,000$ years for zero recoil, and decrease to one per $10,000$ years even for the highest kick velocities of 400 km/s.

That the merging rates derived from evolutionary calculations are by two order of magnitude higher than those based on binary pulsar statistics only, is suggested to be due to the fact that the observable binary pulsars in pairs with NS form only a fraction of the total number of binary NS systems.

The merging rates obtained imply the expected detection rate of binary BH by a LIGO-type gravitational wave detector comparable with and even higher than the binary NS merging rate for a wide range of parameters. Detecting the final frequency of a merging event at about 100 Hz and the shaping of the waveforms would bring a firm evidence of BH existence in nature.

Key words: Pulsars: general – stars: evolution – stars: neutron – stars: black holes

1 INTRODUCTION

Among about 700 known radiopulsars (rapidly rotating, magnetized NS), several tens are observed in binary systems (Taylor et al. 1993). The secondary companion to a pulsar in a binary system can be one of most classes of known celectial bodies: another NS (Hulse & Taylor 1975), a white dwarf (Wright & Loh 1986), a giant blue star (Johnston et al. 1992), or a planet (Wolszcan & Frail 1992).

The formation of a NS during the supernova explosion is usually accompanied by a catastrophic mass loss, which in most cases leads to the binary system disruption; a young NS can thus "remember" the orbital velocity of the progenitor star before the collapse of the order of a few 100 km/s ("Blaauw mechanism", Blaauw 1961; Gott et al 1970). However, the range of stellar

parameters (masses, radii, orbital separations etc.) is so wide that some part of the systems must survive as binaries during the cataclysmic processes of stellar collapse (see Bhattacharia & van den Heuvel 1991). In the framework of the standard scenario of binary system evolution (see van den Heuvel 1994 for a review) diverse species of pulsars are produced and the mean velocities of radiopulsars of about 100-200 km/s that were measured shortly after their discovery (Manchester & Taylor 1977) can be naturally explained by high mass loss during the supernova explosion.

Resent revision of the pulsar distance scale has led to two-fold increase in the mean pulsar transverse velocities derived from pulsar proper motion (Lyne & Lorimer 1994): they now become as high as 400 km/s. Independently, even higher pulsar birth velocities of $\sim 500 - 900$ km/s has been found from studying young pulsar positions inside the associated supernova remnants (Frail et al. 1994). To explain this, the idea of an asymmetrical supernova collapse proposed by Shklovskii (1970) has been reanimated.

Since Lyne & Lorimer's distribution for pulsar transverse velocities is based on the distance scale model, it may be controversial and it has been suggested that no natal kick velocity is needed to fit the pulsar velocity data (see, e.g. Iben & Tutukov 1996). In the present paper we show, using quite independent arguments, that the surprising diversity of binary pulsar companions and the presently observed number of such binary pulsars, strongly contradicts to the hypothesis of the high birth pulsar velocities, generally because such velocities would result in a much more effective disruption of binary systems. However, in contrast to Iben & Tutukov (1996), we show that the observational data does require a kick velocity distribution with the mean value of about 150 km/s and a long power-law high-velocity tail.

We further calculate the effect of the kick velocity on the merging rate of binary relativistic stars (NS+NS, NS+BH, BH+BH), which are among the primary targets for gravitational wave observatories currently under construction (LIGO, VIRGO, GEO-600) (Abramovici et al. 1992; Schutz 1996). Such systems are observed in the Galaxy if one of the components shines as a radiopulsar. Several binary pulsars with massive compact secondary companions are known to date: PSR 1913+16, PSR 1534+12, PSR 0655+64, PSR 2303+46 (see Table 18 in van den Heuvel 1994) and recently discovered PSR J1518+4904 (Nice, Sayer & Taylor 1995), of which two first have orbital periods ≤ 10 hr and will merge due to gravitational radiation losses within less than the age of the Universe $\sim 15 \times 10^9$ years.

It is very important to know the accurate rate of such events, as the planned LIGO sensitivity will allow detection of NS+NS mergings out to ~ 200 Mpc (Abramovici et al. 1992). The problem seems even more actual in view of modern cosmological models of gamma-ray bursts involving binary NS or NS+BH coalescences (Blinnikov et al. 1984, Lipunov et al. 1995). Attempts to estimate this rate (R_{ns}) in our Galaxy have been constantly made over last 20 years using theoretical considerations (Clark et al. 1979, Lipunov et al. 1987, Narayan et al. 1991, Tutukov & Yungelson 1993, Lipunov et al. 1995, Dalton & Sarazin 1995) and binary pulsar observations (Phinney 1991, Curran & Lorimer 1995). The estimations based only on the existing binary pulsar statistics can place an ultraconservative lower limit of 1 per $\sim 10^6$ year, whereas those based on theoretical evolutionary considerations always produce two order of magnitude higher rates of 1 per 10^4 year (see discussion in van den Heuvel 1994). Obviously, the difference comes from the fact that, by deriving the merging rate from pulsar statistics, one should rigorously take into account different selection effects (such as pulsar beaming, completeness of pulsar surveys, possibility of both components to be non-pulsars, etc.). Clearly, an accurate account for the spin evolution of magnetized NS is needed here.

A criticism of the theoretical evolutionary estimates is usually made with the reference to a large number of poorly determined parameters of the evolutionary scenario for massive binary systems, such as common envelope stage efficiency, initial mass ratio distribution, distribution of the recoil velocity imparted to NS at birth, etc. (Lipunov et al. 1996). However, by comparing the results of the Scenario Machine calculations with other observations (Lipunov, Postnov, Prokhorov (hereafter LPP) 1996a,b) we may fix some free parameters (such as the form of the initial mass ratio distrbution and the common envelope efficiency), and then examine the dependence of the double NS merging rate on one free parameter, say the mean kick velocity value. In fact, the calculations turn out to be most sensitive to just the kick velocity (LPP 1996b) as the binary system gets more chances to be disrupted during supernova explosion, especially when the recoil velocity becomes higher than the orbital velocity of stars in the system.

In this paper we also compute the ratio of binary NS with active pulsars to the total number of binary NS, and find the dependence of the binary NS merging rate on the recoil velocity acquired by NS at birth assuming different distributions for this velocity. A recent study of such a dependence was done by Portegies Zwart & Spreew (1996); they, however, examined only a Maxwellian kick velocity distribution, whereas the observations of Lyne & Lorimer (1994) imply a different law for kick velocity (see below).

A special attention is given to calculating galactic NS+BH and BH+BH mergings (R_{bh}). For zero kick velocity this rate is found to be at least 1-2 orders of magnitude smaller than that of NS+NS (eg. Tutukov & Yungelson, 1993). However, the formation of a BH in a binary system may be accompanied by a smaller recoil and, hence, the kick velocity would have a smaller effect on the NS+BH merging rate. Thus we may expect a smaller difference between the two rates if the mean kick velocity is as high as indicated by pulsar proper motions (of order 400 km s^{-1} or more). This in turn would imply that the BH+BH rate might be equally important from the point of view of gravitational wave registration by the LIGO type detectors, since, having at least a few time higher masses, BH binaries may be observed from about ten times farther distances by a detector with given sensitivity (characteristic dimensionless strain metric amplitude from a merging binary system, h_c, scales as $M^{5/6}/r$, where M is a characteristic mass of binary companions and r is a distance to the source (Abramovici al. 1992)). Therefore the number of events registered by the detector scales as

$$\frac{N_{bh}}{N_{ns}} \approx \left(\frac{R_{bh}}{R_{ns}}\right)\left(\frac{M_{bh}}{M_{ns}}\right)^{15/6}$$

and may well be of order unity for typical $M_{bh} \sim 10 M_{\odot}$. We address this question in more detail in a separate paper (Lipunov et al. 1997).

2   THE MODEL

Monte-Carlo simulations has shown its ability to study successfully the evolution of a large ensemble of binaries and to estimate the number of binaries at different evolutionary stages. This method has become popular over last ten years (Kornilov & Lipunov 1984; Dewey & Cordes 1987; Bailes 1989; for another applications of Monte-Carlo simulations see de Kool 1992; Tutukov & Yungelson 1993; Pols & Marinus 1994).

For modeling binary evolution, we use the "Scenario Machine", a computer code based on modern binary evolution scenarios (for a review, see van den Heuvel (1994)), which also takes into account the influence of magnetic field of compact

objects on their observational appearance. A detailed description of the computational techniques and input assumptions is summarized elsewhere (LPP 1996a), and here we list only the basic parameters and initial distributions.

2.1 Initial binary parameters

The initial parameters determining binary evolution are: the mass of the primary ZAMS component, M_1; the binary mass ratio, $q = M_2/M_1 < 1$; the orbital separation, a. We assume zero initial eccentricity.

The distribution of initial binaries over orbital separations is known from observations (Abt 1983):

$$f(\log a) = \text{const},$$

$$\max\ \{10\ \text{R}_\odot,\ \text{Roche Lobe}\ (M_1)\} < \log a < 10^4\ \text{R}_\odot.$$

(1)

The initial mass ratio distribution in binaries, being very crucial for overall evolution of a particular binary system (Trimble 1983), has not yet been reliably derived from observations due to a number of selection effects. A 'zero assumption' usually made is that the mass ratio distribution has a flat shape, i.e. the high mass ratio binaries are formed as frequently as those with equal masses (e.g. van den Heuvel 1994). Ignoring the real distribution, we parametrized it by a power law, assuming the primary mass distribution to obey the Salpeter mass function (Salpeter 1955):

$$\frac{dN}{dM_1} = 0.9\text{yr}^{-1} M_1^{-2.35},\quad 0.1\ \text{M}_\odot < M_1 < 120\ \text{M}_\odot\,;$$

$$f(q) \propto q^{\alpha_q},\qquad\qquad q \equiv M_2/M_1 < 1\,;$$

(2)

This distribution produces approximately 1 massive star ($M_1 > 10\ \text{M}_\odot$) per 60 year in a binary system (assuming 50% stars in the Galaxy in binaries), which coincides with the binary birthrates derived from observations (Popova et al., 1982)

A comparison of the observed X-ray source statistics with the predictions of the current evolutionary scenarios indicates (LPP 1996a) that the initial mass ratio should be strongly centered around unity, ($\alpha_q \sim 2$). Of course, this is not a unique way of approximating the initial binary mass ratio (see e.g. Tout (1991)). However, from the point of view of binary NS merging rate, this parameter affects the results much less than the kick velocity. In the present paper, we use both $\alpha_q = 2$ and $\alpha_q = 0$.

2.2 Initial parameters of compact stars

We are interested in binary NS or NS+BH systems, so it is enough to trace evolution of binaries with primary masses $M_1 > 10 M_\odot$ which are capable of producing NS and BH in the end of evolution. The secondary component can have a mass from the whole range of stellar masses $0.1 M_\odot < M_2 < 120 M_\odot$.

We consider a NS with a mass of 1.4 M$_\odot$ to result from the collapse of a star with the core mass prior to the collapse $M_* \sim (2.5 - 35)$ M$_\odot$. This corresponds to an initial mass range $\sim (10 - 60)$ M$_\odot$, considering that a massive star can loose more than $\sim (10 - 20)\%$ of its initial mass during the evolution with a strong stellar wind (de Jager 1980).

The magnetic field of a rotating NS largely defines the evolutionary stage the star would have in a binary system (Schwartzman 1970; Davidson & Ostriker 1973; Illarionov & Sunyaev 1975). We use a general classification scheme for magnetized objects elaborated by Lipunov (1992).

Briefly, the evolutionary stage of a rotating magnetized NS in a binary system depends on the star's spin period P (or spin frequency $\omega = 2\pi/P$), its magnetic field strength B (or, equivalently, magnetic dipole moment $\mu = BR^3/2$, where R is the NS radius), and the physical parameters of the surrounding plasma (such as density ρ and sound velocity v_s) supplied by

the secondary star. The latter, in turn, could be a normal optical main sequence (MS) star, or red giant, or another compact star). In terms of the Lipunov's formalism, the NS evolutionary stage is determined by one or another inequality between the following characteristic radii: the light cylinder radius of the NS, $R_l = c/\omega$ (c is the speed of light); the corotation radius, $R_c = (GM/\omega^2)^{1/3}$; the gravitational capture radius, $R_G = 2GM/v^2$ (where G is the Newtonian gravitational constant and v is the NS velocity relative to the surrounding plasma); and the stopping radius R_{stop}. The latter is a characteristic distance at which the ram pressure of the accreting matter matches either the NS magnetosphere pressure (this radius is called Alfven radius, R_A) or the pressure of relativistic particles ejected by the rotating magnetized NS (this radius is called Schwartzman radius, R_{Sh}). For instance, if $R_l > R_G$ then the NS is in the ejector stage (E-stage) and can be observed as a radiopulsar; if $R_c < R_A < R_G$, then so-called propeller regime is established (Illarionov & Sunyaev 1975) and the matter is expelled by the rotating magnetosphere; if $R_A < R_c < R_G$, we deal with an accreting NS (A-stage), etc. These inequalities can easily be translated into relationships between the spin period P and some critical period that depends on μ, the orbital parameters, and accretion rate $\dot{M}$ (the latter relates v, v_s, ρ, and the binary's major semiaxis a via the continuity equation). Thus, the evolution of a NS in a binary system is essentially reduced to the NS spin evolution $\omega(t)$, which, in turn, is determined by the evolution of the secondary component and orbital separation $a(t)$. Typically, a single NS embedded into the interstellar medium evolves as $E \rightarrow P \rightarrow A$ (for details, see Lipunov & Popov 1995). For a NS in a binary, the evolution complicates as the secondary star evolves: for example, $E \rightarrow P \rightarrow A \rightarrow E$ (recycling), etc.

When the secondary component in a binary fills its Roche lobe, the rate of accretion onto the compact star can reach the value corresponding to the Eddington luminosity $L_{Edd} \simeq 10^{38}$ $(M/\mathrm{M}_\odot)$ erg/s at the R_{stop}; then a supercritical regime sets in (not only superaccretors but superpropellers and superejectors can exist as well; see Lipunov 1992).

If a BH is formed in due course of the evolution, it can only appear as an accreting or superaccreting X-ray source; other very interesting stages such as BH + radiopulsar which may constitute a notable fraction of all binary pulsars after a starburst are considered in Lipunov et al. (1994, 1995a).

The initial distribution of magnetic fields of NS is another important parameter of the model. This cannot be taken from studying pulsar magnetic field (clearly, pulsars with highest and lowest fields are difficult to observe). In the present calculations we assume a flat distribution for dipole magnetic moments of newborn NSs

$$f(\log \mu) = \mathrm{const}\,, \quad 10^{28} \leq \mu \leq 10^{32}\ \mathrm{G\ cm}^3\,, \tag{3}$$

and the initial rotational period of the NS is assumed to be 1 ms.

The computations were made under different assumptions about the NS magnetic field decay, taken in an exponential form, $\mu(t) \propto \exp(-t/tau)$, where τ is the characteristic decay time of $10^7 - 10^8$ year. The field is assumed to stop decaying below a minimum value of 10^9 G (van den Heuvel et al. 1986). No accretion-induced magnetic field decay is assumed.

A radiopulsar was assumed to be turned "on" until its period P has reached a "death-line" value defined from the relation $\mu_{30}/P_{death}^2 = 0.4$, where μ_{30} is the dipole magnetic moment in units of 10^{30} G cm^3, and P is taken in seconds.

The mass limit for NS (the Oppenheimer-Volkoff limit) is $M_{OV} = 2.5$ M$_\odot$, which corresponds to a hard equation of state of the NS matter. The most massive stars are assumed to collapse into a BH once their mass before the collapse is $M > M_{cr} = 35$ M$_\odot$ (which would correspond to an initial mass of the ZAMS star ~ 60 M$_\odot$ since a substantial mass loss due

to a strong stellar wind occurs for the most massive stars). The BH mass is calculated as $M_{bh} = k_{bh} M_{cr}$, where the parameter k_{bh} is taken to be 0.3, as follows from the studies of binary NS+BH (Lipunov et al. 1994).

2.3 Other parameters of the evolutionary scenario

The fate of a binary star during evolution mainly depends on the initial masses of the components and their orbital separation. The mass loss and kick velocity are the processes leading to the binary system disruption; however, there are a number of processes connected with the orbital momentum losses tending to bound the binary (e.g., gravitational radiation, magnetic stellar wind).

2.3.1   Common envelope stage

We consider stars with a constant (solar) chemical composition. The process of mass transfer between the binary components is treated according to the prescription given in van den Heuvel (1994) (see LPP (1996a) for more detail). The non-conservativeness of the mass transfer is treated via "isotropic re-emission" mode (Bhattacharya & van den Heuvel 1991). If the rate of accretion from one star to another is sufficiently high (e.g. the mass transfer occurs on a timescale 10 times shorter than the thermal Kelvin-Helmholz time for the normal companion), or the compact object is engulfed by a giant companion, the common envelope (CE) stage of the binary evolution can set in (see Paczyński 1976; van den Heuvel 1983).

During the CE stage, an effective spiral-in of the binary components occurs. This complicated process is not fully understood as yet, so we use the conventional energy consideration to find the binary system characteristics after the CE stage by introducing a parameter α_{CE} that measures what fraction of the system's orbital energy goes, between the beginning and the end of the spiralling-in process, into the binding energy (gravitational minus thermal) of the ejected common envelope. Thus,

$$\alpha_{CE} \left(\frac{G M_a M_c}{2 a_f} - \frac{G M_a M_d}{2 a_i} \right) = \frac{G M_d \left(M_d - M_c \right)}{R_d} , \tag{4}$$

where M_c is the mass of the core of the mass loosing star of initial mass M_d and radius R_d (which is simply a function of the initial separation a_i and the initial mass ratio M_a / M_d), and no substantial mass growth for the accretor is assumed (see, however, Chevalier 1993). The less α_{CE}, the closer becomes binary after the CE stage. This parameter is poorly known and we varied it from 0.5 to 10 during calculations.

2.3.2   High and low mass-loss scenario form massive star evolution

A very important parameter of the evolutionary scenario is the stellar wind mass loss effective for massive stars. No consensus on how stelar wind mass loss occurs in massive stars exist. So in the spirit of our scenario approach we use two "extreme", in a sense, cases. The "low mass-loss" scenario treats the stellar wind from a massive star of luminosity L according to de Jager's prescription

$$\dot{M} \propto \frac{L}{c v_\infty}$$

where c and v_∞ are the speed of light and of the stellar wind at infinity, respectively. This leads to at most 30 per cent mass loss for most massive stars.

Table 1. Observational zoo of the field galactic binary pulsars

Type	Number	Fraction	Assumed origin	Reference
PSR+NS	4	0.7%	From massive main sequence stars $(M_{(1,2)} > 10 M_\odot)$	Lorimer et al (1995)
PSR+WD	15	2.5%	From massive binary with large initial mass ratio or accretion induced WD-collapse in LMXB	Lorimer et al (1995)
PSR+PL	2	0.3%	From close NS+WD after WD mass loss to $0.001 M_\odot$ by Roche lobe overflow	Wolsczan & Frail (1992); Shabanova T.V. (1995)
PSR+OB	1	0.2%	After first SN explosion in massive binary with radio transparent stellar wind	Johnston et al (1992)
Single PSR	≈ 600	100%	From disrupted binaries	Taylor et al (1993)

The "high stellar wind mass-loss" scenario uses calculations of single star evolution by Schaller et al. (1992). According to these calculations, a massive star lose most of its mass by stellar wind down to 8-10 $M_\odot$ before the collapse, practically independently on its initial mass. In this case we assume the same mechanism for BH formation as for the "low mass-loss" scenario, but only one parameter k_{bh} remains (M_{cr} is taken from evolutionary tracks). Masses of BH formed within the framework of the high mass-loss scenario are thus always less than or about of 8 $M_\odot$.

So far we are unable to choose between the two scenarios; however, recently reported observations of a very massive WR star of 72 $M_\odot$ (Rauw et al. 1996) cast some doubts on very high mass-loss scenario or may imply that different mechanisms drive stellar wind mass loss. However, we shall use the "high stellar wind mass-loss" scenario when studying binary BH formation rates.

3   PHENOMENOLOGICAL KICK VELOCITY

Ozernoy (1965) and Shklovskii (1970) were among the first who noted that the collapse of a normal star into a compact relativistic object can be anisotropical and thus the stellar remnant can acquire a space velocity much higher than that of the progenitor star, which is typically of the order of a few tens km/s. Due to an enormous energy liberated during the collapse, which is comparable with the rest-mass energy of the whole star, $\approx Mc^2$, a small anisotropy $\alpha \simeq 10^{-6}$ would be sufficient for the remnant to leave the Galaxy at all having the velocity $w = \sqrt{2\alpha}\,c$, where c is the speed of light. A number of the anisotropy mechanisms has been proposed: asymmetric neutrino emission in a strong magnetic field during the collapse (Chugai 1984, Bisnovatyi-Kogan 1993); double neutron star formation during the core collapse (Imshennik 1992); tidally induced asymmetric ignition of the white dwarf during the accretion induced collapse (Lipunov et al. 1987), etc. Recent modelling of the core collapse by Burrows, Hayes and Fryxell (1995) makes the neutrino induced asymetry very promisive (see Burrows & Hayes 1995). Thus, similar to the cosmological constant term, the anisotropy was released away (like a jinnee from the bottle) as a possible but not necessary thing.

It seems natural to assume that the kick velocity is arbitrarily directed in space. The value of the kick velocity w can be quite different and may depend on some parameters, such as the magnetic field strength, angular velocity, and so on; first we consider two extreme assumptions of a strongly determined distribution, $f_\delta(w) \propto \delta(w)$ and of a maxwelian-like one,

$$f_m(w) \propto w^2 \exp(-w^2/w_0^2)\,, \tag{5}$$

which is natural to expect if several independent approximately equally powerful anisotropy mechanisms randomly operates. Here w_0 is a parameter which is connected with the mean kick velocity w_m by a relation $w_m = \frac{2}{\sqrt{\pi}} w_0$.

Since the recent results of Lyne & Lorimer (1994) suggest different distribution, we tried to model the cumulative distribution of the transverse pulsar velocities given in their paper. We found that a *3D-distribution* for the kick velocity imparted to a newborn pulsar of the form

$$f_{LL}(x) \propto \frac{x^{0.19}}{(1 + x^{6.72})^{1/2}} \tag{6}$$

where $x = w/w_0$, w_0 is a parameter, fits well the Lyne & Lorimer's 2D-distribution at $w_0 = 400$ km/s. This distribution has a power-law asymptotic behaviour at low velocities ($x \ll 1$), but goes flatter ($\propto x^0.19$) than the Maxwellian one ($\propto x^2$). As the kick velocities of order or less than the orbital velocities of stars are the most important for the binary system fate after the supernova explosion, we can treat the distribution f_{LL} as the extreme case (the Maxwellian form then proves in between this distribution and the delta-function-like form).

In the case of the collapse into a BH (i.e. when the presupernova mass $M_* > M_{cr} = 35 M_\odot$), we assume that the kick velocity is proportional to the mass lost during the collapse:

$$w_{bh} = w \frac{1 - k_{bh}}{1 - \frac{M_{OV}}{M_*}} \tag{7}$$

where $M_{OV} = 2.5 M_\odot$ is the Oppenheimer-Volkoff limit for NS mass. This function satisfies boundary conditions $w_{bh} = 0$ at $k_{bh} = 1$ (when the total mass of the collapsing star goes into a BH) and $w_{bh} = w_{ns}$ once $M_{bh} = M_{OV}$.

4   EFFECT OF THE KICK VELOCITY ON THE BINARY PULSAR POPULATIONS

Let us consider what fraction of different types of binary radiopulsars can be obtained within the framework of the modern evolutionary scenario for binary stars with the supernova collapse anisotropy included. Several attempts of such kind have been made over the last ten years (Kornilov & Lipunov 1984; Tutukov et al. 1984; Dewey & Cordes 1987; Bailes 1989). The existing at that time observational data convicingly pointed to a presence of a small kick velocity of about 70-100 km/s. However, the statistics of binary pulsars at that time was very poor. Of course, all such studies are restricted to considering the evolution of an ensemble of stars initially originated as binaries and not formed due to tidal capture in globular clusters.

We wish to compare the calculated and observed numbers of binary radiopulsars with neutron stars (PSR+NS), white dwarfs (PSR+WD), planets (PSR+PL), and normal OB-stars (PSR+OB). Table 1 lists the observed numbers of such binary pulsars in the galactic disk and depicts their assumed origin.

The results of simulation of 10^8 binaries are presented in Fig. 1. We assumed that in the artificial galaxy we modeled the number of single stars is equal to that entering binaries, with the total stellar mass of the galaxy being $10^{11} M_\odot$. The calculations were performed for the initial mass ratio power α_q ranged from 0 to 2, which resulted in the notable dispersion of the curves for each type of binary pulsars seen in Fig. 1.

Fig. 1 (left panel) shows the dependence of the fraction of different types of binary pulsars among the total number of radiopulsars (coming from both single and disrupted binary stars) on the mean maxwellian kick velocity w_m (three-dimensional). For completeness, we added the computed number of PSR+BH binaries (assuming the critical mass of the

pre-collapsing star to be 35 $M_\odot$ and the mass fraction forming the black hole to be 0.3 after Lipunov et al. (1994)). The upper axis shows the mean transverse *recoil* velocity of pulsars corresponding to the assumed w_m. The right panel shows the same curves obtained for the kick velocity distribution (6) that fits the pulsar transverse velocity distribution given by Lyne & Lorimer (1994). As expected, the increase in the mean kick velocity decreases all binary pulsar fractions. In Fig. 1 the fraction of pulsars with planets (PSR+PL) is reduced by a factor of 10 for clarity.

The non-monotonic character of the PSR+PL curve is explained by the fact that generally a small kick velocity causes the new periastron of the binary system decrease, which makes dissipative processes more efficient and therefore leads to the white dwarf Roche lobe overflow with the subsequent planet formation in a wide binary around a pulsar. At higher kick velocities the number of PSR+PL gradually decreases. A more rapid fall of the PSR+NS and PSR+BH curves is caused by these systems undergoing two collapses (and hence, two kicks).

Obviously, the "maxwellian" curves decreases faster (left panel of Fig. 1) than the "L&L" ones. This is due to a flat power-law asymptotics of Lyne & Lorimer's 2D distribution at low velocities. Indeed, for large mean kick velocities the maxwellian distribution has an asymptotic behaviour $f_m \sim w^2$ at slow velocities (≤ 300 km/s) which are less or comparable with the characteristic binary orbital velocity, whereas $f_{LL} \sim x^{0.19}$ goes much flatter. We also note that calculations for delta-function-like kick velocity distribution (not shown in these figures) naturally lead to even faster drop of the binary pulsar fractions.

Fig. 2 shows the computed fractions of PSR+NS, PSR+WD and PSR+OB among the observable pulsars in the particular case of $\alpha_q = 0$ (flat intitial mass ratio distribution) assuming kick velocity distribution f_{LL} given by Eq.(6). As the fractions are small, we can apply Poissonian statistics to evaluate the significance of the calculations. We draw the confidence levels corresponding to 68.4% (1σ), 95.45% (2σ) and 99.73% (3σ) probabilities. As is seen from the figure, in all three cases the observed numbers (dashed lines) fall within 3σ errors only for the mean kick velocities less than ≈ 200 km/s.

In Fig. 3 we present the 'phase space' cuts coming through the calculated point for Lyne-Lorimer 3D-kick (6) with $w_0 = 400$ km/s. The solid lines show the phase volume boundaries corresponding to 1-5σ confidence levels. The numbers of objects are normalized so as to have 700 single visible pulsars in the modeled galaxy. The observed numbers from Table 1 are shown by the dashed lines. The figure demonstrates that the mean kick velocity 400 km/s lies far outside 5σ level for all types of objects. We find that the combined calculated and observed numbers differ by less than 3 times for the mean kick velocities $w_m < 200$ km/s at ≈ 100 km/s.

Let us turn now to the observable 2D distribution of the pulsar transverse velocities (Lyne & Lorimer 1994; Frail et al. 1994). As mentioned above, it is well reproduced by the law (6) with $w_0 = 400$ km/s, which corresponds to the mean velocity $w_m \simeq 0.83 \times w_0 \approx 332$ km/s (we note that the mean recoil space (3D) velocity of pulsars with such kick distribution is ≈ 370 km/s; obviously, for high velocities kick and recoil velocities coincide with each other). The mean kick velocity that high would correspond to a five-fold disagreement with the observed situation. Higher mean recoil transverse velocities reported by Frail et al. (1994), 500-1000 km/s, would lead to a more dramatic inconsistency. Fig. 1 clearly demonstrates that for high mean space velocities > 300 km/s the observed binary pulsar "Zoo" would rapidly vanich.

As the computed binary pulsar fractions are strongly dependent on the kick velocity, a question arises as to how accurately we derive them from observations. The fraction of binary pulsars among the total single pulsar population seems to be

minimally subjected to possible selection effects. Indeed, let us compare the observable fraction of binary pulsars (Table 1) with pulsar birthrates and galactic numbers derived from pulsar statistics with account of a number of selection effects (Lorimer, 1995; Curran & Lorimer, 1995). For example, Curran & Lorimer (1995) estimate the total number of the potentially observable (i.e. with no account of beaming) NS+PSR pairs in the Galaxy ~ 240. The total number of the potentially observable galactic single pulsars (Lorimer et al., 1993) is estimated to be $1.3 \pm 0.2 \times 10^4$. Hence, the galactic fraction of PSR+NS to PSR is $240/13000 \approx 1.8\%$ with a half-order accuracy, and the observed ratio of 0.5% (Table 1) thus places an *upper limit* to the kick velocity. We note that PSR+NS systems are most sensitive to the kick velocity (because for them the kick effect doubles) and, therefore, they are the most important for our consideration.

The number of PSR+WD systems is less accurately known. For example, if we use the ratio of local birthrate of low-mass binary pulsars $2 - 4 \times 10^{-9}$ kpc^{-2} yr^{-1} (Lorimer, 1995) to the local pulsar burthrate $6 - 12 \times 10^{-6}$ kpc^{-2} yr^{-1} (Lorimer et al. 1993), we would obtain the fraction PSR+WD/PSR $0.4 - 6\%$, assuming the average age of PSR+WD pulsars 100 times that of single PSR. While this figures agrees with our estimate $\sim 2.1\%$ (Table 1), they are very uncertain. Nevertheless, Fig. 1 demonstrates that the observed NS+WD statistics does not contradict an optimal kick velocity value of 150-200 km/s.

To conclude this Section, in Fig. 4 we present the calculated pulsar transverse recoil velocity distribution for three specific cases: with zero kick (curve (1)), the maxwellian kick with $w_m = 150$ km/s and distribution (6) best-fitting Lyne-Lorimer data (shown by filled circles). The cumulative distribution is reproduced for comparison (upper panel). Clearly, the maxwellian distribution is unable to reproduce the high-velocity tail observed in the observed pulsar transverse velocity.

5   FRACTION OF ACTIVE PULSARS IN RELATIVISTIC COMPACT BINARIES

Before proceed to studying the effect of kick velocity on the rate of binary NS/BH mergings, we wish to answer the question: why estimations of merging rates obtained from pulsar statistics are systematically by two orders of magnitude less than those obtained from evolutionary calculations? A possible answer proposed by van den Heuvel (1992) and Tutukov & Yungelson (1993) is that many relativistic compact binaries are formed after the common envelope stage with too short orbital period and hence coalesce on a short time-scale. In our opinion, this is not the case. Our calculations (Lipunov et al., 1996c) and integration of the curve for NS+NS birthrates presented in Fig. 1 of Tutukov & Yungelson's paper show that binary NS+NS with life-time before coalescence less than 10^7 years contributes only $\sim 10 - 20\%$ to the total galactic merging rate.

We propose a more clear explanation connected to the physical state of the rotating NS, becacuse not all NS in relativistic binaries are shining as pulsars. To estimate this effect a thorough treatment of NS spin evolution is needed. The major uncertainty here is whether the magnetic field of NS decay or not.

Fig. 5-6 show the fraction of active binary pulsars with NS component among the total number of binary NS in the whole range of orbital periods for two values of the exponential magnetic field decay time 10^7 and 10^8 years. The "low mass-loss" scenario for stelar wind was used. The calculated fraction is only slightly dependent on the binary orbital period and thus can be considered as an underestimation factor of binary NS merging rate. As seen from Fig. 5-6, this factor is typically of order $1 - 3\%$ for a wide range of the mean kick velocities and common envelope efficiencies. Combined with beaming factor,

this brings the underestimation factor to less than 1%. Thus, the lower limits to the binary NS coalescence rate derived from binary pulsar statistics must be increased by a factor of 100, which reconciles them with theoretical expectations.

6   EFFECT OF THE KICK VELOCITY ON RELATIVISTIC BINARY MERGING RATES

In view of the importance of the kick velocity for evolutionary scenario, in this section we focus on how kick velocity affects the double NS/BH merging rates.

6.1   Low stellar wind mass loss

First we consider the low stellar wind mass-loss evolution. We start with reproducing a typical evolutionary track leading to the formation of a coalescing binary BH (Fig. 7). BH formation parameters are $M_* = 35 M_\odot$ and $k_{bh} = 0.3$. Zero kick velocity is used to compute this track. Each evolutionary stage shown in these figures is marked with masses of components and orbital separation (in solar units). (Everyone can try to construct these and many other tracks under different assumption via WWW-server at the URL `http://xray.sai.msu.su/sciwork/scenario.html`).

Fig. 8 shows merging rates of the relativistic compact binaries as a function of the mean kick velocity assuming different kick distributions (maxwellian or Lyne-Lorimer). The stronger decrease in the case of the maxwellian distribution is due to the steeper dependence ($\sim x^2$) of this distribution at lower velocities. Notice also an increase in the NS+BH merging rate at small velocities and its constancy at higher velocities. From Fig. 8 we see that the theoretical expectation for the NS+NS merging rate in a model spiral galaxy with the total stellar mass of 10^{11} M$_\odot$ lie within the range from $\sim 3 \times 10^{-4}$ yr^{-1} to $\sim 10^{-5}$ yr^{-1}, depending on the assumed mean kick velocity and the shape of its distribution. For zero kick velocity, our results are fully consistent with earlier estimates (Lipunov et al. 1987, Tutukov & Yungelson, 1993).

For Lyne-Lorimer kick velocity law with the mean value of 400 km/s, we obtain $R_{NS+NS} \approx 5 \times 10^{-5}$ yr^{-1}, which again yeilds the estimate of 1 NS+NS merging per $\sim 10,000$ years considering the beaming factor. Note that the event rate of 10^{-5} mergings per year at $w = 450$ km/s was recently obtained by Portegies Zwart & Spreeuw (1996) who assumed a maxwellian distribution for kick velocity. This figure is in line with our calculations (upper line in Fig. 8). We repeat, however, that the maxwellian kick velocity distribution would be in a strong disagreement with binary pulsar fractions even at low kick velocities (see Fig. 1).

Our galactic NS+NS merging rate (5×10^{-5} yr^{-1}) is also exceeds the so-called "Bailes upper limit" to the NS+NS birthrate in the Galaxy $\sim 10^{-5}$ yr^{-1} (Bailes, 1996). Indeed, following Bailes, the fraction of "normal" pulsars in NS+NS binaries which potentially could merge during the Hubble time among the total number of known pulsars is less than $\sim 1/700$. Multiplying this by the present birthrate of "normal" pulsars 1/125 yr-1 (Lorimer et al. 1993), we obtain this limit 10^{-5} yr^{-1}. In contrast, our NS+NS merging rate is 5 times higher for Lyne-Lorimer kick velocity distribution even at $w = 400$ km/s. First we note that the accuracy of the Bailes limit is a half-order at best; in addition, the pulsar birthrate 1/125 yr^{-1} is a lower limit and at least 4 times lower than the birthrate of massive stars ($> 10 M_\odot$) which produce neutron stars in our Galaxy (once per 30 years according to Salpeter mass function).

This discrepancy may be decreased considering the existing uncertainty in the pulsar beaming factor and, which may

be more important, the still-present uncertainty in pulsar distance scale which influences the estimate of the total galactic number of pulsars and hence their birthrate.

In addition, one more important point indicates that the Bailes limit cannot be universal. As our calculations of binary NS+NS merging rate evolution show (Fig. 1 in Lipunov et al., 1995), binary NS formed as long as 10-15 billion years ago ('relic' NS binaries) may coalesce at the present time and their merging rate may exceed the Bailes limit, so the true merging rate should be determined by baryon fraction transformed into the first population stars and has no connection with the currently observed pulsar statistics (the Bailes limit).

Two details from Fig. 8 worth noting: 1) the binding effect at small kick velocities and 2) the smaller effect of high kicks on the BH+NS (BH) rate. The first fact is qualitatively clear: a high kick leads to the system disruption; however, if the system is survived the explosion, its orbit would have a periastron distance always smaller than in the case without kick. During the subsequent tidal circularization a closer binary sytem will form which will spend less time before the merging. The binding effect of small recoil velocities is very pronounced in the case of binary BH. At higher kicks their merging rate decreases slower due to higher masses of the components.

6.2   High stellar wind mass loss

Now we turn to the high stellar wind mass-loss evolution. We recall that within the framework of this scenario, single massive stars lose most their mass by stellar wind to leave a WR star of 8-10 $M_\odot$ and even smaller which then explodes presumably as a SN type Ib and leaves NS or BH as a remnant. Here only one BH formation parameter is needed – k_{bh}.

The results of computing galactic merging rates of binary relativistic stars for $k_{bh} = 0.75$ and different kicks (no kick or Lyne-Lorimer kick with the mean velocity $w = 400$ km s^{-1} are presented in Fig. 9. The rates are plotted against the minimum initial mass of main-sequence star that evolves to form a BH.

7   RELATIVE RATIO OF BINARY BH AND NS MERGING RATES

It is widely recognized that binary BH mergings may be as important as binary NS mergings. Let us make a crude estimation of the BH binary merging rate. Within the framework of our assumptions, the mass of BH progenitor is $35M_\odot$ (if low mass-loss stelar wind is effective), which corresponds roughly to $M_{ms} \sim 60M_\odot$ on the main sequence (we recall that according to the evolutionary scenario, mass of a star after mass transfer is $M_{core} \simeq 0.1M_{ms}^{1.4}$). On the other hand, any star with $M_{ms} \geq 10M_\odot$ evolves to form a NS. Using the Salpeter mass function ($f(M) \propto M^{-2.35}$), we obtain that BH formation rate relates to NS formation rate as $(60/10)^{-1.35} \approx 0.09$. Extrapolating this logic to binary BH/NS systems, we may expect $R_{bh}/R_{ns} \sim 1/10$, within a half-order accuracy. Actually, the situation is complicated by several factors: the presence of the kick velocity during supernova explosion which may act more efficiently in the case of NS formation; mass exchange between the components; distribution by mass ratio, etc. Our calculations account for most these factors.

Fig. 10-11 demonstrate the relative detection rate of coalescing BH and NS binaries obtained by a gravitational wave detector with a given sensitivity. In Fig. 10 we present the relative detection rate assuming the low stellar wind mass loss scenario as a function of BH-formation parameter k_{bh}, the fraction of the stellar mass that forms a BH after the collapse, for two particular initial distirbution of binaries by mass ratio: $\alpha_q = 2$, a strongly peaked toward equal initial masses distribution (as

follows from the independent study of X-ray binaries modeling, LPP 1996a), and $\alpha_q = 0$, a flat initial mass ratio distribution. These calculations were performed assuming both zero kick velocity during supernova explosion (the dashed line in the figure) and Lyne & Lorimer's kick velocity distribution with the mean velocity $w_0 = 400$ km/s. It is seen that the form of the initial mass ratio distribution only slightly affects the results. Thus the ratio of detection rates for merging BH/NS binaries (1) may well exceed unity for a wide range of parameters.

In Fig. 11 we plot the same ratio of BH to NS merging events as in Fig. 10, but calculated for the high stellar wind mass-loss scenario. The parameters are the same as for caculations shown in Fig. 9 ($k_{bh} = 0.75$, Lyne-Lorimer kick with $w = 400$ km s^{-1}). This ratio is plotted as a function of the minimal initial mass of main-sequence star capable of producing a BH in the end of its evolution.

8   DUSCUSSION

8.1   Uncertainties of the results

Three independent groups of factors can potentially affect the results of evolutionary simulations: (1) the assumptions underlying the scenario of binary evolution used; (2) the intrinsic accuracy of Monte-Carlo simulations and (3) selection effects.

(1) Scenario assumptions. The present scenario for the binary star evolution has many parameters, some of which has a purely theoretical sense. Of them, the most crucial are the shape of the initial mass ratio distribution and the kick velocity imparted to neutron stars at birth. While the former was explored in Lipunov et al. (1995b), the latter is studied in the present paper for a wide range of possible kick velocity distributions. From the point of view of the effect the kick has on the binary system evolution, the most crucial proves the low velocity tail of the distribution. Having chosen the Maxwellian (5) and Lyne & Lorimer laws (6), we thus studied power indexes of the low velocity asymptotics from the range 0.19-2.

Another important question is how the magnetic field of neutron stars is distributed and how it evolves. Unfortunately, the initial magnetic field distribution for neutron stars cannot be directly taken from pulsar observations because of strong selection effects for highest and lowest magnetic fields, so in the present calculations we have chosen the broadest possible initial magnetic field distribution ($d \log \mu = const$). Then, we assumed exponential field decay. The results shown in Fig. 5-10 were obtained for a decay time of 100 Myr. Taking $\tau = 10^7$ yr does not alter appreciably the calculated fractions of binary pulsars (especially PSR+NS), unless one assumes a strong dependence of pulsar magnetic fields on the evolutionary history (see Camilo et al. 1994). This may have effect on the pulsars originated from low-mass binary systems. However, the example of Her X-1, which provides evidence of a high magnetic field in an accreting low-mass binary system, shows that one should consider such possibilities with caution, and in the present work this complication of the evolutionary scenario is not taken into account.

At last, for very massive stars from which BH are formed the crucial is how fast stellar wind mass loss occurs. We specially used both high and low stellar wind mass-loss cases when studying BH formation as two extremal scenarios for binary evolution.

(2) The intrinsic accuracy of Monte-Carlo simulations is determined by the number of trials which in our case is 10^6 per each run, so expected errors are much less than the scenario uncertainties.

(3) Selection effects. These are important for comparison with observations. In estimating the ratios of binary pulsars, one may argue that different selections affect the numbers of single and binary pulsars (e.g. Johnston & Kulkarni 1990), for example, that the recycled pulsars may constitute a larger fraction among single pulsars than is actually observed. In this case, however, we use a *lower limit* of the actual binary pulsar fractions, and thus obtain *conservative* results, as increasing the observed fractions of binary pulsars would aggravate the problem of high mean kick velocities implied by recent pulsar observations (Fig. 1). When we derive binary pulsar mass fractions using pulsar birthrates given by Lorimer et al. (1993), Lorimer (1995) and Curran & Lorimer (1995) (especially for NS+PSR fraction), we again obtain even smaller kick velocity $\sim 80 - 100$ km/s.

8.2   Does the nature require an ad hoc asymmetric kick?

In the recent paper, Iben & Tutukov (1996) try to explain self-consistently the observational pulsar data without invoking an ad hoc kick velocity imparted to neutron star at birth. They criticize the Lyne & Lorimer's data referring to the pulsar distance scale uncertainties. In fact, the Lyne & Lorimer's distribution has two characteristic features: (1) a very high *mean* velocity (at least two times higher than that was believed earlier) and (2) an unusually long power-law tail of pulsar velocities (in contrast to, for example, the exponential tail in a Maxwellian distribution). Our consideration shows that the high mean space velocity of pulsars is in a paradoxical contradiction with the observed Zoo of binary pulsars. In this sense, our conclusions coincide with Iben & Tutukov's ones (no high kick velocity). However, we insist on that if the mean kick velocity decreases keeping the qualitative behavior of the pulsar velocity distribution (i.e. the power-law high-velocity tail, which does not relate to the assumed distance scale and therefore does not depend on selective effects of this kind), we have to invoke the kick hypothesis.

This fact, as well as the best coincidence between observations and calculations at $w \sim 100 - 200$ km s−1, indicate the need for a small natal kick velocity, as was previously shown by Kornilov & Lipunov (1984). We recall that in the latter paper the authors relied upon the lack of the observed binary pulsars with OB-stars at that time, and this difficulty could be overriden by assuming, as Iben & Tutukov (1996) do, that the pulsar phenomenon appears only for neutron stars born in close binary systems with orbital periods smaller than ~ 10 days. But in the present paper we use all variety of the observed pulsars and, what is especially important, their relative number with respect to single pulsars, which in no ways can be reduced within the framework of the hypothesis that no pulsars appears in wide binary systems. Therefore, our statistical analysis of pulsar numbers, together with the observation of the high-velocity power-law tail in pulsar velocity distribution, makes the assumption of the presence of a moderate kick velocity quite realistic.

In addition to the statistical arguments, there is a lot of independent observational indications of the moderate kick velocity existence. For example, the observed inclination of the gaseous disk around Be-star in PSR B1259-63 relative to the orbital plane (Melatos et al. 1995) could hardly arise without supernova explosion asymmetry. Many observed long-term variability in classical X-ray binaries (such as Her X-1, SS 433, LMC X-4, etc., see Cherepashchuk (1981)) may be quantitatively expalined in a natural way if the first supernova explosion in these systems was asymmetric. At last, a direct evidence for a kick velocity of at least 100 km/s has recently been obtained from observations of precessing binary pulsar orbit in PSR J0045-7319 in the SMC (Kaspi et al. 1996).

9   CONCLUSION

The purposes of the paper was to study the effect of kick velocity (1) on the observed numbers of binary pulsars with different companions and (2) on the the expected merging rates of binary relativistic stars – double NS, NS+BH and double BH systems.

1. The calculations presented above demonstrate a strong decrease in number of binary pulsars with diverse secondary components as a function of the assumed kick velocity imparted to a neutron star at birth. On the other hand, high birth velocities of pulsars seem to be really observed (Lyne & Lorimer 1994; Frail et al. 1994). Thus, a paradoxical situation emerges: we have to make a choice between the high birth space velocities for the pulsars and the observed reach Zoo of binary pulsars in the galactic disk! Unless the observational data are subjected to a number of selection effects leading to an underestimation of low-velocity pulsars (e.g. Tutukov et al. 1984), a possible outcome from this paradoxical situation could be a slow steady acceleration of neutron stars which would not disrupt the binary system, but would impart a high space velocity to single pulsars (for example, a rocket mechanism by Tademary & Harrison (1975) caused by an asymmetric pulsar emission). However, the evidence for high velocities of young pulsars associated with supernova remnants (Frail et al. 1994) and the lack of a firm evidence for the velocity increasing with age are not consistent with this mechanism. The presence of numerous pulsars in globular clusters also put constraints on the efficiency of such a mechanism.

What to do with the fast pulsars moving with velocities > 1000 km/s? The highest pulsar velocities resulted from the disruption of a neutron star – massive helium star binary during a spherically-symmetric collapse of the helium star cannot be greater than $\sim 700 - 800$ km/s. Recently suggested mechanism by Bisnovatyi-Kogan (1993) allows the birth pulsar velocities as high as 3000 km/s, but still requires a very strong magnetic field ($B \gg B_{cr} \simeq 4.4 \times 10^{13}$ G) at birth; Imshennik's (1992) mechanism of double neutron star formation during the collapse with the subsequent Roche lobe overflow of the less massive neutron star and its explosion after a minimum mass of about 0.1 $M_\odot$ has been reached, although does not need the magnetic field that high, could lead to very high individual space velocities, but hardly to the high *mean* kicks required to fit the observations. A promising could also be the mechanism of anisotropic neutrino emission during the supernova explosion recently suggested by Burrows & Hayes (1995). These mechanisms will be checked after the gravitational waves detection will have been possible by future LIGO/VIRGO experiments.

We conclude that the observed diversity and the number of the binary pulsars, while do require a small kick velocity ($\sim 100 - 200$ km/s) to be present, are, at the same time, in a strong contradiction with the presently derived high mean transverse velocities of pulsars.

2. We also studied how the merging rate of relativistic binary compact stars (NS+NS, NS+BH, BH+BH), which are amongst the primary targets for future LIGO type gravitational wave detectors, depends on some crucial parameters of the modern evolutionary scenario of binary stellar systems, namely on the common envelope efficiency α_{CE} and mean recoil velocity imparted to NS at birth. Assuming the Salpeter law for primary mass, a flat initial binary mass ratio, a flat magnetic field distribution of young NS and its exponential decay on a timescale of $10^7 - 10^8$ yrs, we obtained that the galactic number of binary NS with orbital periods $P < 10$ hrs is at least a factor of 100 higher than that deduced from binary pulsar statistics

(Phinney 1991, Curran & Lorimer 1995). We also obtained that this rate decreases nearly exponentially with mean kick velocity. The decrease goes faster in the case of maxwellian disribution for kick velocity. Currently popular Lyne-Lorimer kick velocity law that yeilds the observed pulsar transverse velocity distribution would give the binary NS merging rate of 5×10^{-5} per year even for extremely high kick velocity $w = 400$ km/s. The merging rate for NS+BH and BH+BH binaries was found to be about 10^{-5} per year per Galaxy and practically insensitive to the kick velocity for $w > 100$ km/s.

We conclude that the relativistic compact binary merging rate, even for high mean kick velocities of NS up to 400 km/s, leads to at least 30-50 such events per year from within a distance of 200 Mpc, which the LIGO detectors will be sensitive to. The high merging rate of relativistic binaries with BH implies that it is not excluded that a comparable (and even probably a major) fraction of all events that will be registered by LIGO detectors may be due to these events. This urges efforts on numerical modeling BH+BH coalescences to obtain template wavefroms from such process.

ACKNOWLEDGEMENTS

REFERENCES

Abramovici, A. et al. 1992, Science 256, 281
Abt, H., 1983, ARAA 21, 343
Bailes, M. 1989, ApJ 342, 917
Bailes, M. 1996, in "Compact Stars in Binaries", Eds. J.A. van Paradijs, E.P.J. van den Heuvel and E. Kuulkers, Kluwer Acad. Publ., Dordrecht, p.213
Bhattacharia, D. & van den Heuvel, E.P.J. 1991, Phys. Rep. 203, 1
Bisnovatyi-Kogan, G.S. 1993, Astron. Astrophys. Trans. 3, 287
Blaauw, A. 1961, Bull. Astron. Inst. Netherlands 15, 265
Blinnikov, S.I., Novikov, I.D., Perevodchikova, T.V. & Polnarev, A.G. 1984, SvA Lett. 10, 177
Burrows, A., Hayes, J. & Fryxell, B.A. 1995, ApJ 450, 830
Burrows, A. & Hayes, J. 1995, Phys. Let. sumbitted (SISSA preprint # astro-ph/9511106)
Camilo, F., Thorsett, S.E. & Kulkarni, S.R. 1994, ApJ 421, L15
Chanmugam, G. 1992, ARA&A 30, 143
Cherepashchuk, A.M. 1981, Pis'ma AZh 7, 726
Chevalier, R.A. 1993, ApJ 411, L33
Chugai, N.N. 1984, SvA Lett. 10, 210
Cordes, J.M. 1986, ApJ 311, 183
Curran, S.J. & Lorimer, D.R. 1995, MNRAS 276, 347
Dalton, W.W. & Sarazin, C.L. 1995, ApJ 440, 280
Davidson, K. & Ostriker, J.P. 1973, ApJ 179, 585
Dewey, R.J.& Cordes, J.M. 1987, ApJ. 321, 780
Frail, D.A., Goss, W.M. & Whiteoak, J.B.Z. 1994, ApJ 437, 781
Gott, J.R., Gunn, J.E. & Ostriker, J.P. 1970, ApJ 160, L91
Hulse, R.A. & Taylor, J.H. 1975, ApJ 195, L51
Iben, I.,Jr. & Tutukov, A.V. 1984, ApJ 284, 719
Iben, I.,Jr. & Tutukov, A.V. 1996, ApJ 456, 738
Illarionov, A.F. & Sunyaev, R.A. 1975, A&A 39, 185
Imshennik, V.S. 1992, Pis'ma AZh 18, 489
de Jager, C. 1980, "The Brightest Stars", D.Reidel, Dordrecht
Johnston, H.M. & Kulkarni, S.R. 1992, ApJ 368, 504
Johnston, S. et al. 1992, ApJ 387, L37
Kaspi, V.M., Bailes, M., Manchester, R.N., Stappers, B.W., Bell, J.F. 1996, Nature 381, 584

de Kool, M. 1992, A&A, 261, 188

Kornilov, V.G. & Lipunov, V.M. 1984, AZh, 61, 686

Lipunov, V.M. 1992, "Astrophysics of Neutron Stars", Springer Verlag, Heidelberg

Lipunov, V.M. & Popov, S.B. 1995, AZh 72, 711

Lipunov, V.M. & Postnov, K.A. 1987, Ap.& Sp.Sci. 145, 1

Lipunov, V.M., Postnov, K.A. & Prokhorov, M.E. 1987, A&A 176, L1

Lipunov, V.M., Postnov, K.A., Prokhorov, M.E. & Osminkin, E.Yu. 1994, ApJ 423, L 121

Lipunov, V.M., Postnov, K.A., Prokhorov, M.E., Panchenko, I.E. & Jorgensen, H.E. 1995, ApJ 454, 593

Lipunov, V.M., Postnov, K.A. & Prokhorov, M.E. 1996a, A&A 310, 489

Lipunov, V.M., Postnov, K.A. & Prokhorov, M.E. 1996b, Astrophys. Space Phys. Reviews, Ed. by R.A.Sunyaev (Harwood Acad. Publishers, Amsterdam), v.9 part 4, 178 pp.

Lipunov, V.M., Postnov, K.A. & Prokhorov, M.E. 1996c, New Astronomy, in press.

Lipunov, V.M., Postnov, K.A. & Prokhorov, M.E. 1997, submitted to Pis'ma Astron. Zh.

Lorimer, D.R., Bailes, M., Dewey, R.J. & Harrison, P.A. 1993, MNRAS 263, 403

Lorimer, D.R. 1995, MNRAS 274, 300

Lorimer, D.R. et al.1995, ApJ 439, 933

Lyne, A.G. & Lorimer, D.R. 1994, Nature 369, 127

Manchester, R.N. & Taylor, J.H. 1977, Pulsars (W.H.Freeman and Company, San Francisco)

Melatos, A., Johnston, S. & Melrose, D.B. 1995, MNRAS 275, 381

Ozernoy, L.M. 1965, JETP Lett. 2, 52

Phinney, E.S. 1991, ApJ 380, L17

Paczyński, B. 1976, in "Structure and Evolution of Close Binary Systems, IAU Symp. No. 73, Eds. Egglton, P.P., Mitton, S.A., & Whealan, J.A.J., Reidel, Dordrecht, 75

Pols, O. & Marinus, M. 1994, A&A 288, 475

Portegies Zwart, S.F. & Spreew, J.N. 1995, A&A (in press)

Rappaport, S.A., Joss P.C., & Webbink, R.F. 1982, ApJ 254, 616

Rauw G., Vreux J.-M., Gosset, E. et al. 1996, A&A 306, 771

Salpeter, E.E. 1955, ApJ 121, 161

Schaller, G., Schaerer D., Meynet, G., et al. 1992, A&ASS 96, 269

Schwartzman, V.F. 1970, Radiofizika 13, 1850

Shabanova, T.V. 1995, ApJ 453, 779

Shklovskii, I.S. 1970, AZh 46, 715

Tademary E. & Harrison E.R. 1975, Nature 254, 39

Terman, J.L. & Taam, R.E. 1995, MNRAS 276, 1320

Taylor, J.H., Manchester, R.N. & Lyne, A.G. 1993, ApJSS 88, 529

Tout, C.A. 1991, MNRAS 250, 701

Trimble, V. 1983, Nature 303, 137

Tutukov, A.V., Chugai, N.N. & Yungelson, L.R. 1984, SvA Lett. 10, 244

Tutukov, A.V. & Yungelson, L.R. 1993, MNRAS 260, 675

van den Heuvel, E.P.J. 1983, in "Accretion Driven Stellar X-ray Sources", Eds. Lewin, W.H.G. & van den Heuvel, E.P.J. Cambridge Univ. Press, 303

van den Heuvel, E.P.J., van Paradijs, J.A. & Taam, R.E. 1986, Nature 322, 153

van den Heuvel, E.P.J. 1992, in "X-Ray Binaries and Recycled Pulsars", Eds. E.P.J. van den Heuvel and S.A. Rappaport, Kluwer Acad. Publ., Dordrecht, p.233

van den Heuvel, E.P.J. 1994, in "Interacting Binaries", Eds. Shore, S.N., Livio, M., & van den Heuvel, E.P.J. Berlin, Springer, p.442

Verbunt, F. & Zwaan, C. 1981, A&A 100, L7

Wolszcan, A. & Frail, D.A. 1992, Nature 355, 145

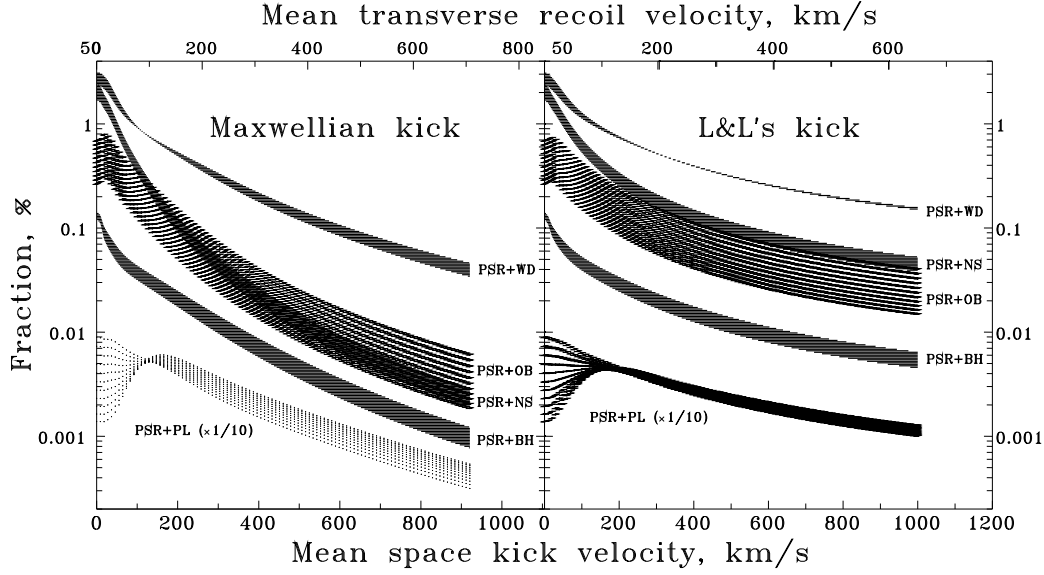Wright, G.A. & Loh, E.D. 1986, Nature 324, 127

Figure 1. Binary pulsar fractions among the total number of pulsars as a function of the mean kick velocity for a maxwellian distribution (right panel) and Lyne-Lorimer distribution (left panel). The width of each curve reflects the variation in the power index $0 \leq \alpha_q \leq 2$ of the initial mass ratio spectrum. The curve for pulsars+planets is shifted down by one order of magnitude for clarity.
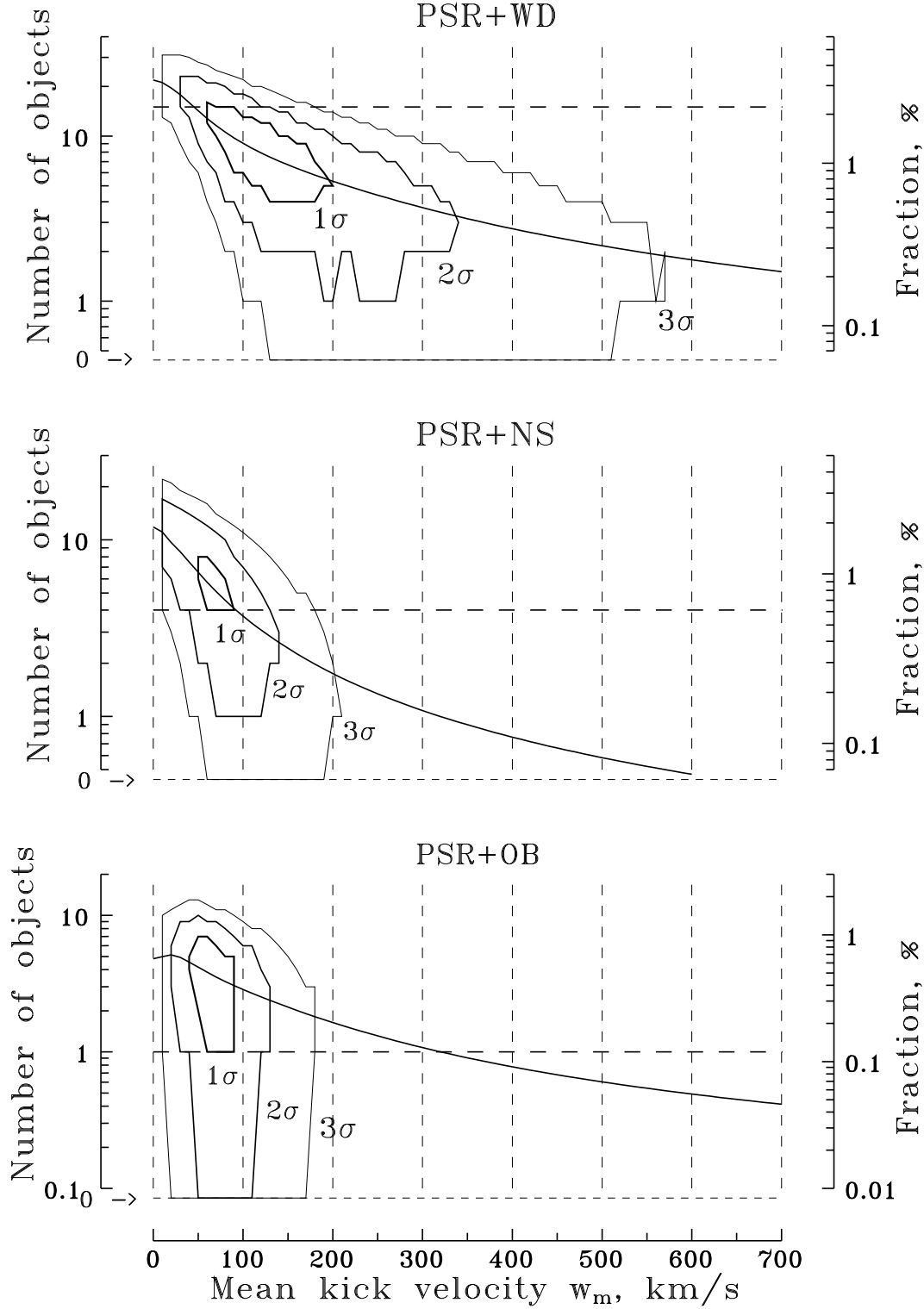
Figure 2. Number and fraction of PSR+WD (a), PSR+NS (b) and PSR+OB (c) systems (for $\alpha_q = 0$) as a function of the mean kick velocity distributed according to the law (6) that produces pulsars transverse velocities fitting the Lyne & Lorimer's data. Shown also are 1σ, 2σ and 3σ errors computed assuming Poissonian statistics of binary pulsar numbers among the total number of visible pulsars. The observed fractions are shown by the dashed line.
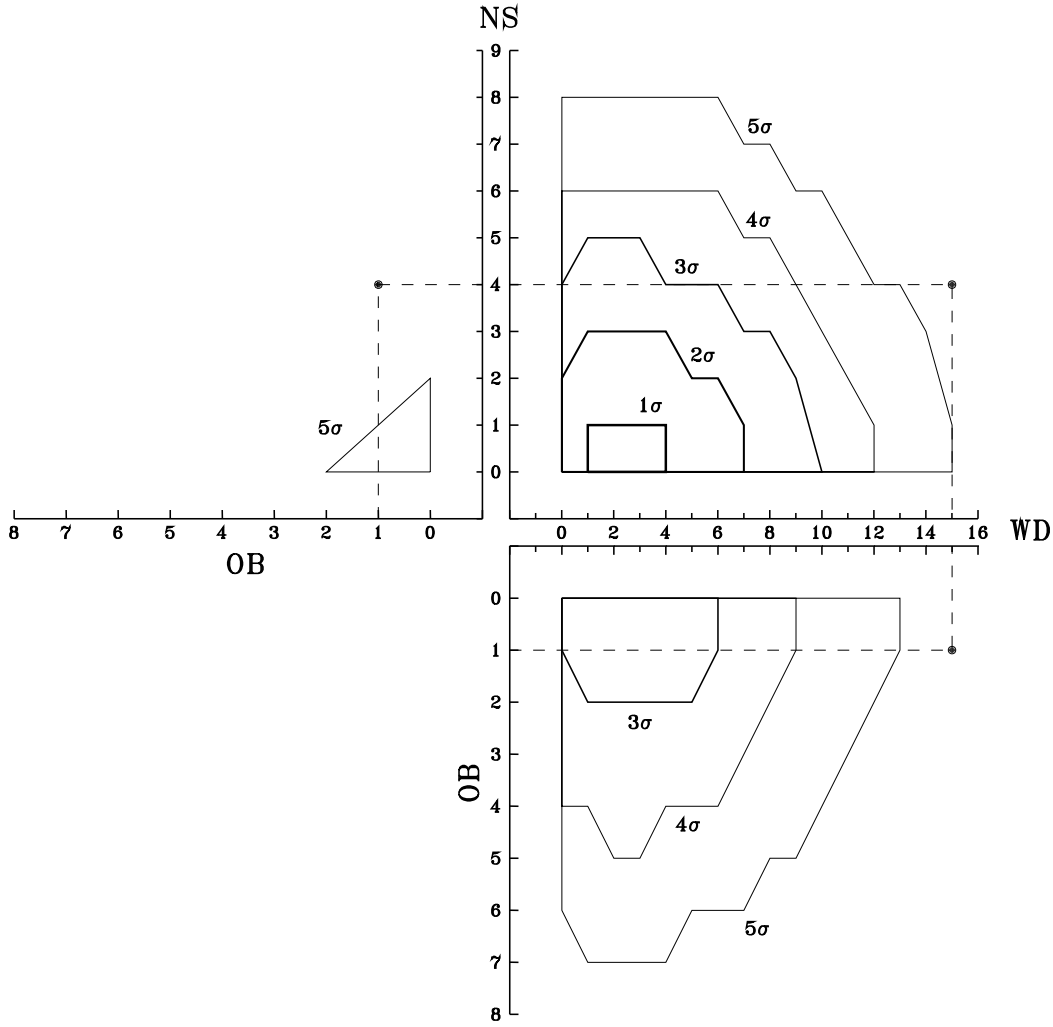
Figure 3. The cross-sections of 'phase space' by the plane coming through the calculated point corresponding to Lyne & Lorimer's 3D-kick (6) at $w_0 = 400$ km/s. Solid lines show boundaries of the phase volume corresponding to 1-5σ confidence level. The numbers of objects are normalized so as to have 600 single visible pulsars in the modelled galaxy. The observed numbers from Table 1 are shown by the dashed lines.
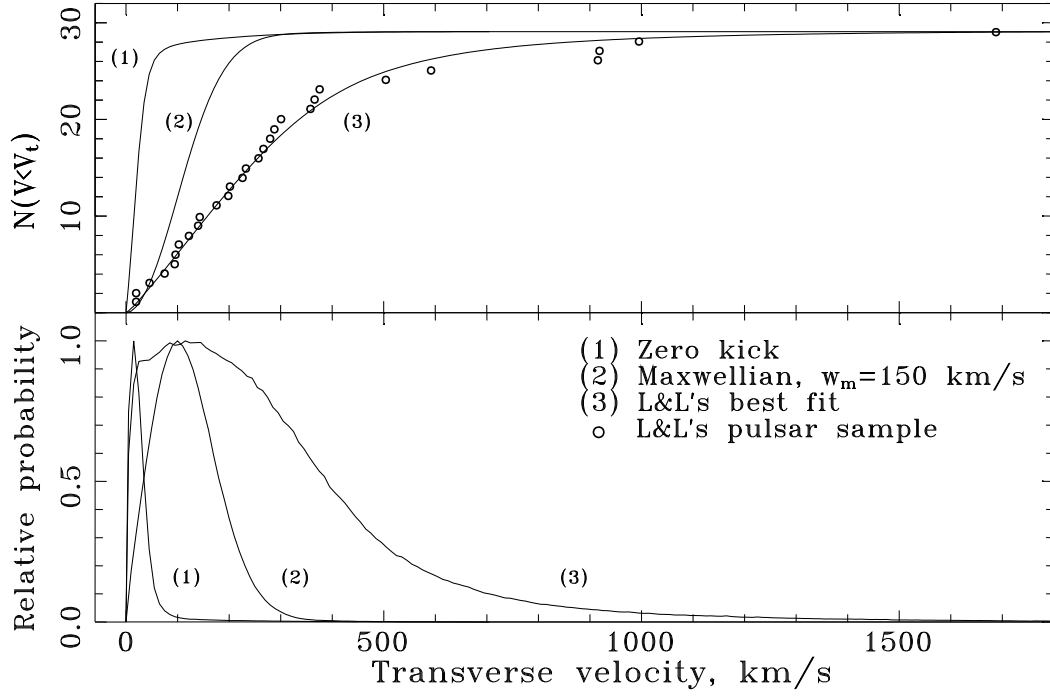
Figure 4. The simulated pulsar transverse velocity distribution (bottom panel) and cumulative distribution (upper panel) for different kicks. The dots are the observed cumulative distribution from Lyne & Lorimer (1994).
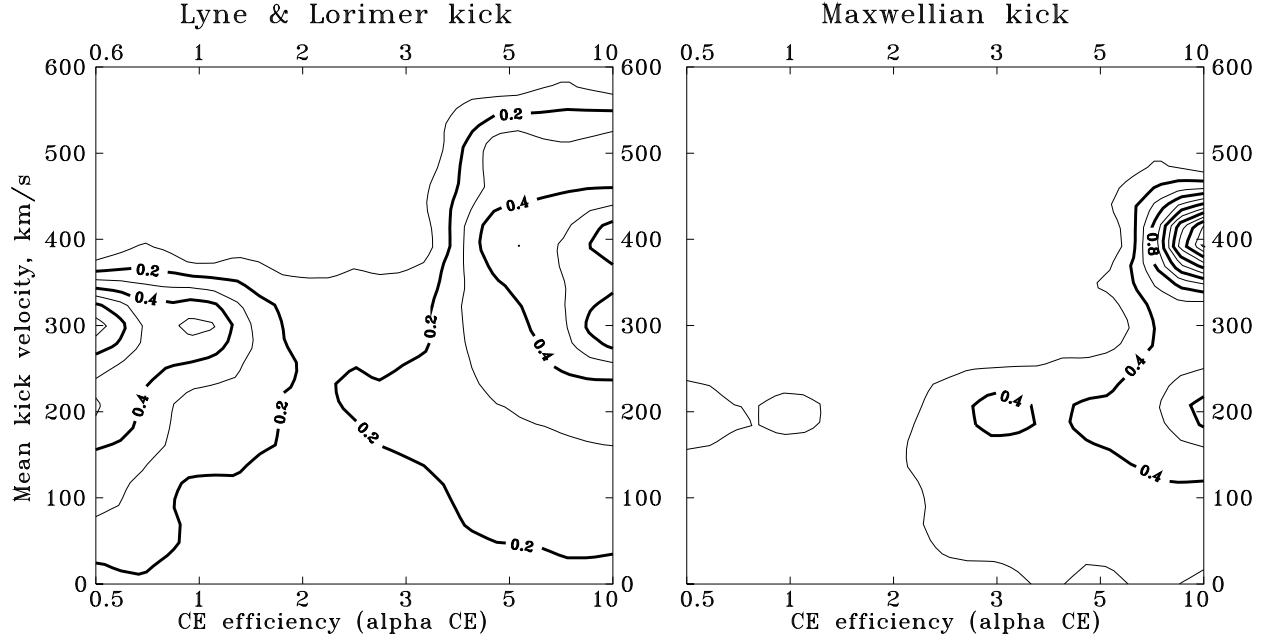
Figure 5. The percentage of binary pulsars with NS companions among all NS+NS binaries as a function of the common envelope efficiency α_{CE} and mean kick velocity w_m for maxwellian (right panel) and Lyne-Lorimer kick velocity distributions assuming an exponential magnetic field decay on the characteristic timescale $t_d = 10^7$ years
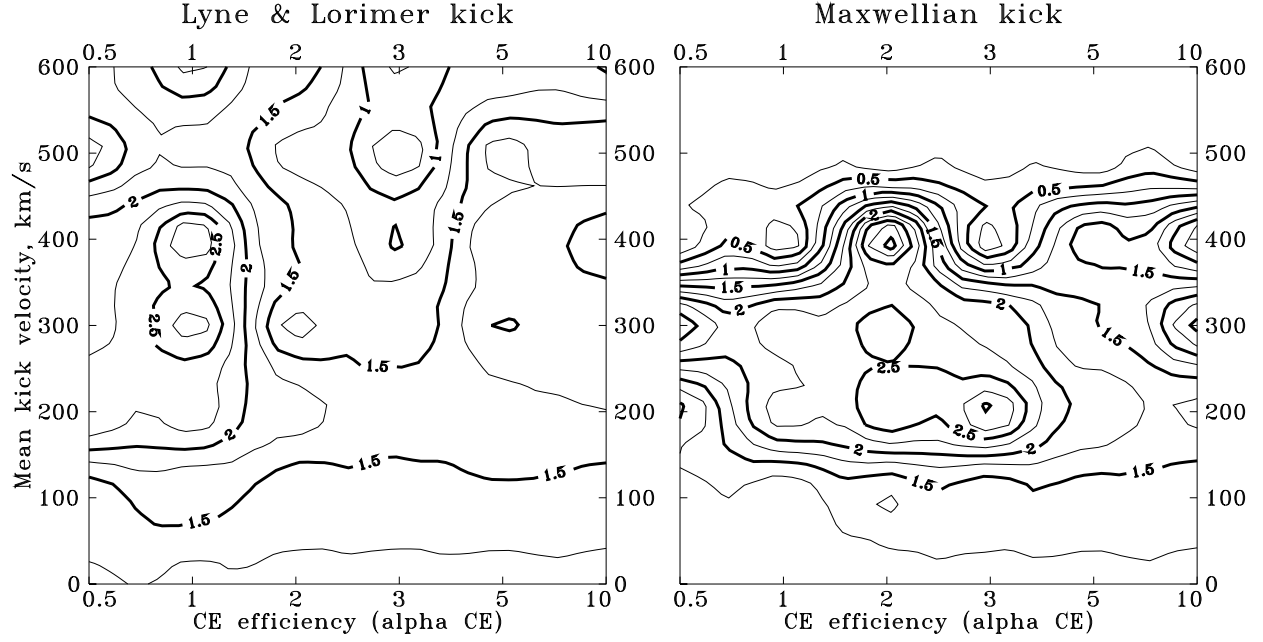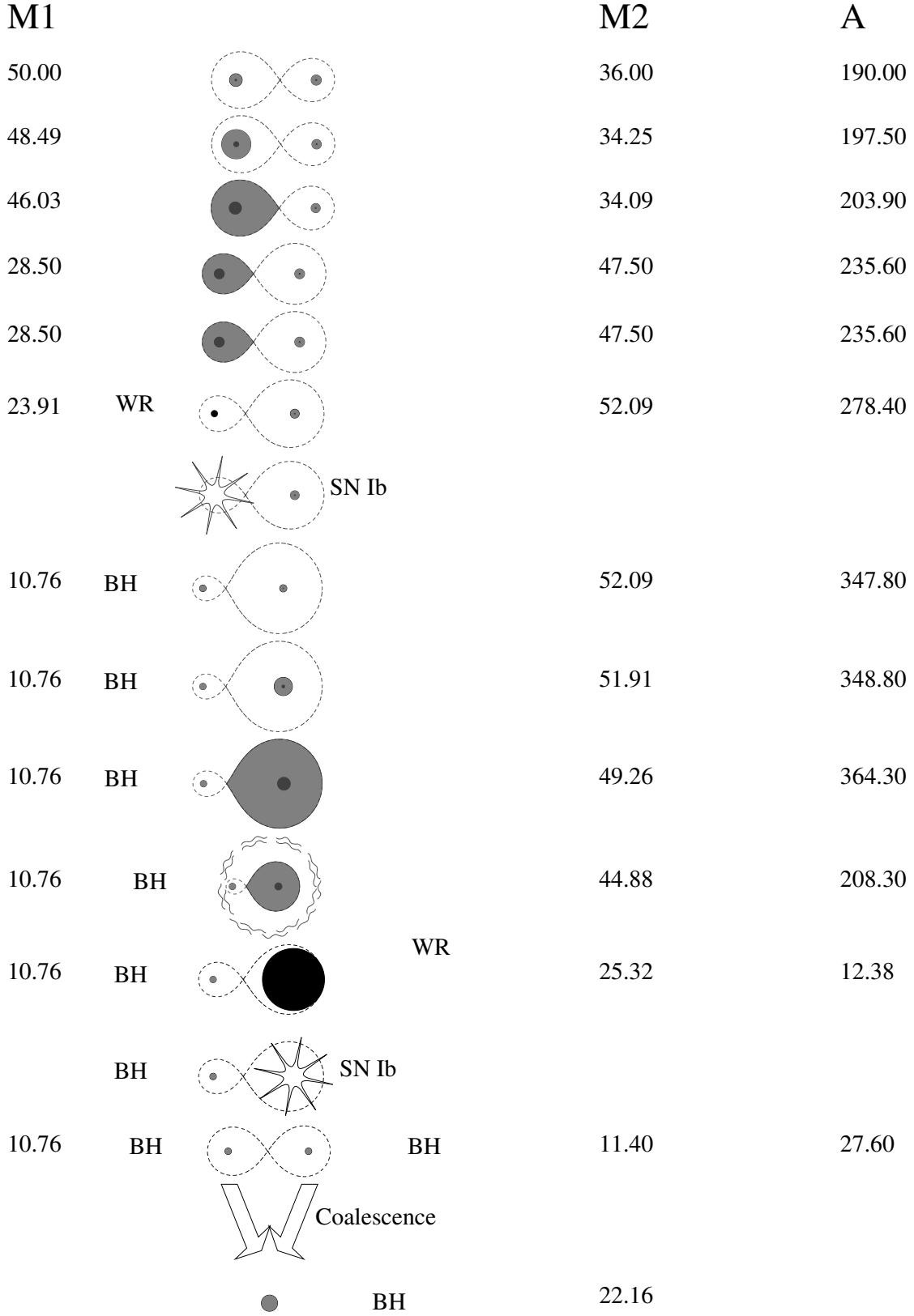
Figure 6. The same as in Fig. 5 for $t_d = 10^8$ years

M1		M2	A
50.00		36.00	190.00
48.49		34.25	197.50
46.03		34.09	203.90
28.50		47.50	235.60
28.50		47.50	235.60
23.91	WR	52.09	278.40
	SN Ib		
10.76	BH	52.09	347.80
10.76	BH	51.91	348.80
10.76	BH	49.26	364.30
10.76	BH	44.88	208.30
10.76	BH	WR 25.32	12.38
	BH SN Ib		
10.76	BH BH	11.40	27.60
	Coalescence		
	BH	22.16	

Figure 7. Example of a binary BH system formation
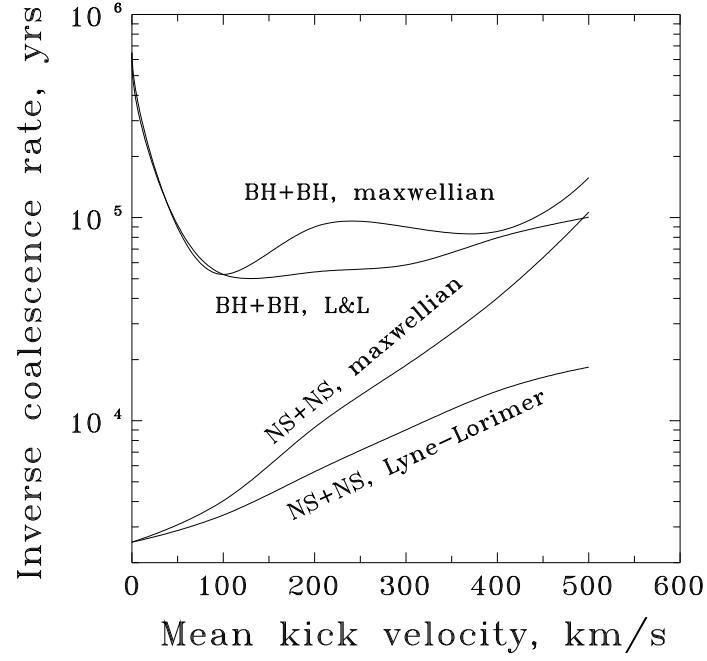
Figure 8. The total merging rate of NS+NS and BH+BH binaries for different kick velocity laws for $t_d = 10^8$ yr and assuming low stellar wind mass-loss.
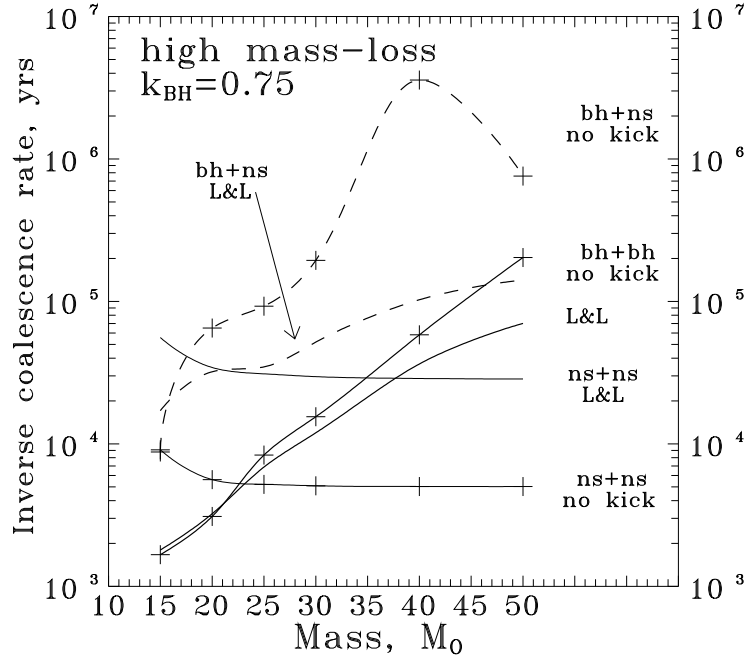
Figure 9. The merging rate of NS+NS, NS+BH and BH+BH binaries for different kick velocity assumptions for the high stellar wind mass-loss scenario as a function of the minimum mass of main-sequence star producing BH in the end of evolution.
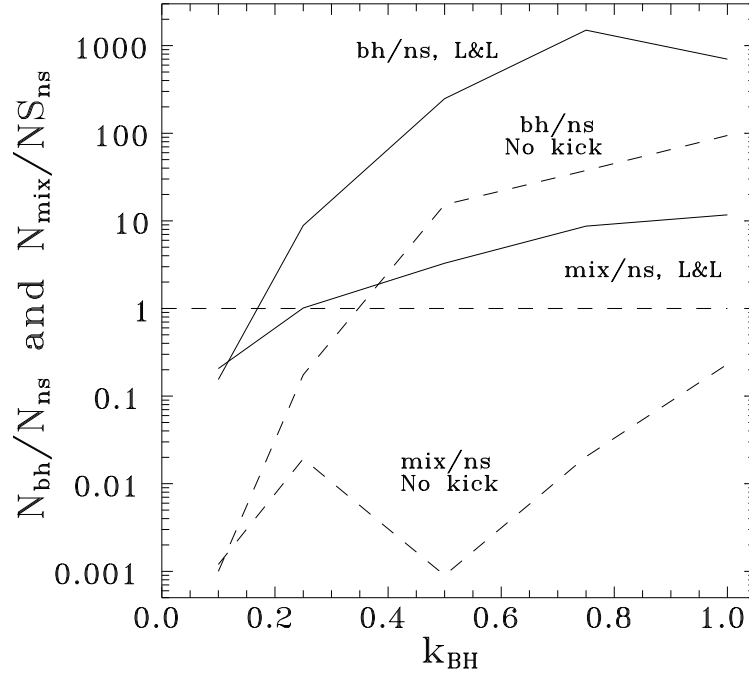
Figure 10. The ratio of NS+BH and BH+BH mergings relative to NS+NS events detected by a gravitational wave detector with a given sensitivity, as a function of parameter k_{bh} assuming low stellar wind mass-loss scenario. Calculations with Lyne-Lorimer kick velocity distribution and without kick are shown by solid and dashed lines, respectively.
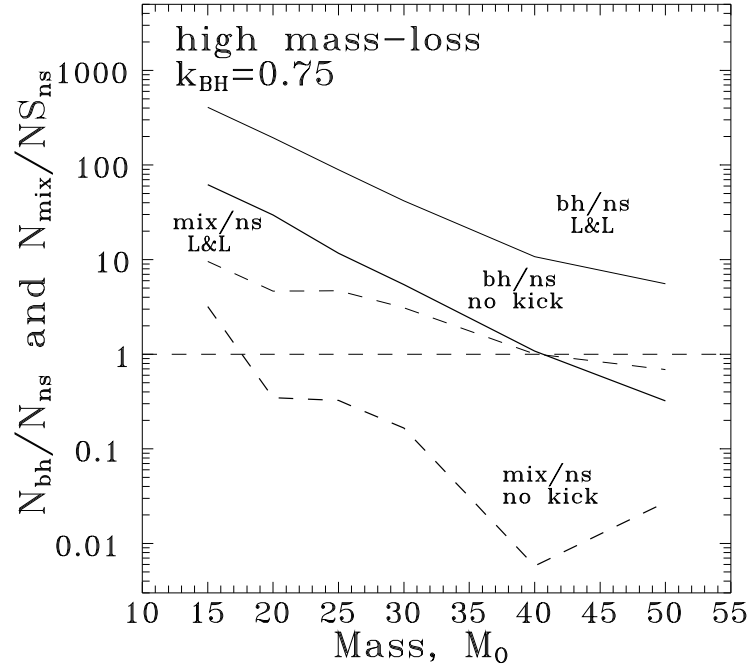
Figure 11. The ratio of NS+BH and BH+BH mergings relative to NS+NS events detected by a gravitational wave detector with a given sensitivity, as a function of minimal mass of a main sequence star producing black hole for different kick velocity laws (not specified for NS+BH and BH+BH binaries in the figure) within the framework of high stellar wind mass-loss scenario.